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NASA's Human Lunar Landing Strategy

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Abstract

In early 2020, NASA's Human Landing System Program made awards to a set of American companies to compete for the design, delivery and demonstration of an integrated human landing system to land the next Americans near the South Pole of the Moon by 2024. Awards were made utilizing the NextSTEP Broad Agency Announcement procurement mechanism and kicked off a seven-month Certification Baseline Review, leading up to a Continuation Review and possible down-select by NASA at the end of 2020. This paper discusses the work that has been done thus far for the rapid development of a human landing system to safely carry the first woman and the next man to the lunar surface. It will also provide a preview of the work that remains ahead for the program.
Keywords: Artemis, Human Landing System, Mars, Moon, Propulsion

1. Introduction

In response to the ambitious exploration goals set forth by Space Policy Directive-1 to "lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars," [1] NASA's human lunar exploration program, Artemis, will land the first woman and the next man on the surface of the Moon by 2024 and establish sustainable exploration by the end of the decade. These lunar missions will help the Agency prepare for humanity's next giant leap—sending astronauts to Mars. [2]

Through the Human Landing System (HLS) Program, NASA is working with commercial companies to design and develop the landers that will deliver the first woman and next man to the Moon in 2024, with an eye toward global lunar access and reusable landing systems. The innovation of the private sector is key to NASA's goal of sustainable lunar exploration.

On April 30, 2020, utilizing the Next Space Technologies for Exploration Partnerships (NextSTEP) Broad Agency Announcement procurement mechanism, NASA made awards to three American companies to compete for the design, delivery and demonstration of an integrated human landing system: a Blue Origin-led team with Lockheed Martin, Northrup Grumman, and Draper; Dynetics (a Leidos company); and SpaceX. These firm-fixed price, milestone-based contracts were awarded for a 10-month base period during which each company, together with NASA, has refined their lander concepts and determined standards and requirements that will ensure the designs can be certified for human spaceflight.

Concurrent with the base period, NASA is running the procurement for the next phase of HLS development, Option A, which will determine which human landing system design(s) will be selected to continue development to flight. After receiving proposals from the three base period contractors in late 2020, NASA will award up to two Option A contracts, providing a seamless transition to the next phase of development that ultimately culminates in crewed demonstration missions to the lunar surface, beginning with the Artemis III mission in 2024.

The capabilities determined and developed during the initial Artemis missions will feed forward toward the development of sustainable human landing systems that will support the long-term exploration and development of the Moon and enable NASA to successfully conduct future missions to Mars. Throughout the 2020s, NASA will develop increasingly larger, more capable, reusable human landing systems that can land more precisely and carry more cargo, in addition to using robotic landers to deliver infrastructure critical to a long-term sustainable presence on the Moon such as vehicles and habitats.

Recognizing that exploration of the Moon and Mars is intertwined, NASA is prioritizing investments in Artemis lunar exploration today that will support successful future human exploration of Mars, designing and testing common Moon-Mars systems and maturing technologies needed for sending astronauts to Mars, including human landing systems. [3]

2. The Moon-to-Mars approach

Integrated Moon-to-Mars programs date back at least to Werner von Braun's 1952-1954 series of *Collier's* magazine articles that were lavishly illustrated by Chesley Bonestell [4,5,6]. Von Braun's articles provided factual, detailed descriptions of spaceships and launch vehicles, based on work he had already done and was currently doing at the Redstone Arsenal in Huntsville, Alabama, and began to tie together a program of human exploration that included low-Earth orbit space stations, lunar lander and bases and crewed Mars missions. Von Braun's 1952 initial lunar lander featured nitric acid and hydrazine engines and a crew of 50, and was followed by his 1954 Mars lander design that featured a winged "landing plane" that carried crews to an aircraft-style landing on the red planet, using the 1952 lunar lander as its in-space propulsion stage (see Fig. 1). While these landers shared limited commonality, the utility and logic of an integrated Moon-Mars program was introduced.

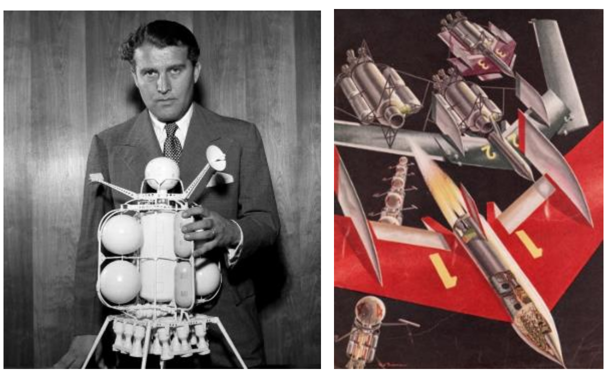

Fig. 1. Werner von Braun with his 1952 lunar lander concept, and the Chesley Bonestell 1954 concept art for a winged Mars lander

Just weeks after the successful completion of the Apollo 11 mission, von Braun presented an Integrated Exploration Program proposal to the Space Task Group [7] that built on the success of Apollo, called for a space shuttle and Earth-orbiting space station and pressed for a human landing on Mars as early as 1981. Von Braun's lunar lander concepts evolved the successful Lunar Module, eventually expanding to a modular base with a crew of 48. The Mars lander evolved from earlier winged vehicles to a more classic Apollo Command Module shape (see Fig. 2) using blunt-body aerodynamic deceleration and hypergolic propulsion to carry 3 crewmembers to the Martian surface for a 30-60-day mission.

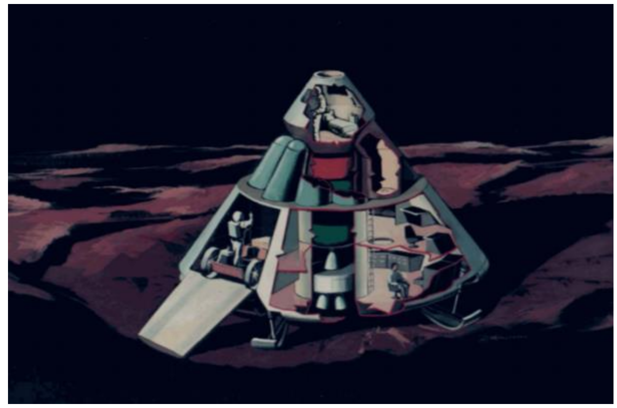

Fig. 2. von Braun 1969 Mars Excursion Module

The next attempt to integrate a lunar and Mars exploration program, and the vehicles required for such, was 1989's Space Exploration Initiative (SEI), and the vehicles described in NASA's "90 Day Study" [8]. The study began to show extensibility from the Lunar Excursion Vehicle to the Mars Excursion Vehicle—though physically different, both featured common cryogenic propulsion systems with the aim of utilizing In-Situ Resource Utilization (ISRU)-derived propellants from both the Moon and Mars. The SEI's lunar excursion vehicle was sized to deliver 33 metric tons to the lunar surface in an expendable cargo-only mode or four crew and 13-15 metric tons of cargo plus a crew module in a piloted mode. The Mars transportation system supported a piloted mission mode to deliver a crew of four and 25 metric tons of payload to the surface of Mars. The Mars excursion vehicle crew module design was based on the lunar excursion vehicle crew module to support the crew during descent and provide spartan crew accommodations for up to 30 days to cover contingencies in activating a surface habitat.

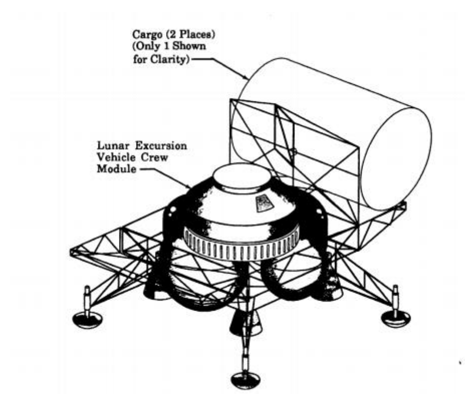

Fig. 3. Space Exploration Initiative Lunar Excursion Vehicle (1989)

2004 brought the Vision for Space Exploration and a Presidential directive to revive NASA's Moon-Mars exploration activities. This resulted in a new architecture with a common theme—use of the Moon as a testbed for Mars exploration. The Exploration Systems Architecture Study (ESAS) [9], which formed the basis for the ensuing Constellation Program, defined a lunar lander system that utilized methane-oxygen ascent propulsion and ISRU for lunar refueling. Both of these technologies would be tested on the Moon to support a future Mars lander that would also use liquid oxygen (LOX)-methane propulsion and ISRU refueling. These propulsion choices were made to link lunar and Mars propulsive elements for the purpose of risk reduction, and further linked to the ISRU technology experiments that were to be performed on the planetary surfaces by precursor robotic missions.

Fig. 4. Exploration Systems Architecture Study: Propulsion and ISRU maturation path from the Moon to Mars

Recent Space Policy Directives, guidance from the National Space Council [10,11] and NASA's internal Artemis planning have continued to define human lunar exploration programs as development testbeds to future human Mars exploration. Many of these links are in the area of heavy-lift boosters, in-space propulsion and habitation and surface systems. While different in physical appearance, lunar and Mars lander systems will share common technologies such as ISRU-compatible propulsion, guidance and navigation systems and crew systems. NASA's initiative to have commercial vendors build and design elements such as human landing systems may also have an impact on how these technologies feed forward from lunar vehicles to Mars landers.

NASA's current human Mars mission plans are described by Smith et al. in NASA's Path from Low-Earth Orbit to the Moon and to Mars [12].

3. Common Moons-Mars lander investments

Through the Artemis program, NASA expects to gain significant Mars-forward experience from lunar human landing systems, such as storable propellant solutions and advanced terrain-relative navigation technologies for precision landing and hazard avoidance.

3.1 Propulsion

Lunar-Martian investments by the HLS program will allow for several new propulsion technologies to be demonstrated. This includes liquid oxygen (LOX), liquid hydrogen (LH2) and liquid methane/liquid natural gas (LCH4/LNG) propulsion systems across several thrust classes. The engines being developed will be able to demonstrate in-space performance and landing operation robustness. The advancement will provide the space community with a more robust inventory of available options with which commercial partners can work for future space exploration missions.

Different propellant management operations, including transfer and management, will also be demonstrated by the HLS program. The technologies demonstrated will enable space exploration sustainability goals covering several different cryogenic fluid management technologies as well. Both active and passive cryogenic fluid management variants have different solutions that can provide flight data to further improve future exploration missions. These data will directly affect and inform propulsion system architecture and design, enabling consideration of LH2 and LCH4/LNG systems for longer duration missions such as those to Mars.

While supersonic retro propulsion (SRP) is an additional challenge for Mars due to the atmosphere, investments are already being made in NASA's Space Technology Mission Directorate (STMD) to model and characterize the impact of the flow on the vehicle and the payload. Specific investments to convert computational fluid dynamic (CFD) codes to run on supercomputers is already reducing the CFD calculation time from years to days. Validation of the CFD using wind tunnel tests for entry vehicles of interest are currently under way.

3.2 Precision landing

Guidance, navigation and control algorithms and sensors, as well as design philosophies for approach and landing, can be tested at the Moon. Common on-board high-performance computing capabilities employed in various aspects of the lunar architecture may offer equally significant impacts and opportunities for Mars missions. Some examples include performing guidance trajectory Monte Carlo calculations onboard during entry, descent and landing (EDL) and enabling the use of high-performance sensors, such as terrain relative navigation, that can process measurements in a fraction of the time. These aspects critical to Mars EDL can be demonstrated at the Moon. Several such guidance algorithms and navigation sensors designs are currently under development.

In addition to the hardware, software, technology and operation commonalities for Moon and Mars missions, the EDL community strives to maintain the human capital commonality, namely individuals who have worked both Mars EDL architecture studies and lunar mission design and implementation. Other efforts to maintain common simulation frameworks, which are constantly updated to incorporate latest model data and perform analysis, are ongoing. Maintaining corporate knowledge of the goals of multiple destination architectures is also critical to a Mars-forward philosophy.

3.3 Crew cabin

The crew cabin is another example of a required capability that is similar for both lunar and Mars missions. As a critical part of the vehicle that transports the crew to and/or from a planetary surface, the basic functions of the crew cabin include: 1) providing pressurized habitability for the crew members, such as environmental control, sleep accommodations, waste management and safety equipment; 2) allowing ingress and egress on the surface and when docking to orbital assets; 3) accommodating logistics, consumables, scientific equipment and returned samples; 4) facilitating manual control of the vehicle during mission operations; and 5) supporting other functions such as extravehicular activity (EVA) operations and dust mitigation.

Artemis human landing system crew cabin designs being considered transfer the crew from Orion or Gateway to the lunar surface and back, a round-trip approach that could be used for Mars missions. However, because the impulse, or change in velocity (ΔV), required to travel between the Martian surface and Mars orbit is approximately twice that needed for lunar missions, current reference Mars mission architectures being developed by NASA utilize separate vehicles for descent and ascent [13] and vehicle staging on ascent. The current NASA designs for the Mars Ascent Vehicle (MAV) utilize propellants produced in-situ on the Martian surface, and the MAV we be fully fueled and operational before committing the crew to the surface, another aspect that drives the architecture to use separate vehicles. Despite these architectural differences, the crew cabin used for such transfers and the subsystems needed can possess significant commonality.

3.3.1 Crew size and mission duration

Crew size and mission duration are key factors in designing a crew cabin for any space mission, dictating the volume required to support the crew. In support of the Artemis III mission, the HLS crew cabin is being designed to accommodate two crew members for up to a total of eight Earth-days (6.5 Earth-days on the lunar service) without any pre-deployed assets. The mission would also support: 1) delivery of 865 kg (threshold) and 965 kg (goal) from lunar orbit to the surface; 2) return of at least 525 kg from the surface to lunar orbit; and 3) return a scientific payload of at least 35 kg (threshold) and 100 kg (goal), inclusive of tare.

The same crew cabin is anticipated to accommodate four crew members during sustained lunar operations, but will only support the in-space, landing and ascent portions of the mission given that assets such as habitats and pressurized rovers will be delivered to the surface [14].

This pre-deployment approach is also planned for Mars missions. Although the crew size and operational staging orbits for Mars missions are still being traded, a crew size of four with durations of up to approximately three Earth-days is anticipated [15]. As such, the total crew durations for both missions are very similar, and the volume required for the lunar missions should support the Mars missions along with the landing and return capabilities associated with HLS crew cabin design.

3.3.2 Crew cabin design and operation

As for any deep space destination, there will be unique aspects to crew cabin design. For example, recumbent seats are not necessarily needed for the lower gravity and thrust levels associated with lunar missions and communication delay times will be much shorter than for Mars missions. However, many of the crew cabin subsystems and components that support a Mars mission, including the power generation and storage system, thermal control, thermal, debris and radiation protection, Environmental Control and Life Support System (ECLSS), Waste Management System (WMS), avionics (communications, displays and controls) and EVA interfaces and support have similar performance requirements and can share commonality with a lunar human landing system or be directly evolved from it.

The operational lifetime of the crew cabin for Mars missions is likely to approach ten years with up to half of that time spent on the Martian surface in a quiescent state. The implementation of a reusable HLS in support of increasing lunar surface durations and supported by pre-deployed assets provides a cumulative operational and quiescent durations that are very much consistent with the times required for Mars missions.

Although many strategies for dust mitigation can be implemented and synergistically combined, the crew cabin represents the final step in the process and is ultimately where the crew will be exposed directly to any dust that has been transported back into the pressurized volume. This was a significant issue for the Apollo astronauts due to the EVA suits being brought directly into the crew cabin. A Mars crew cabin's systems (e.g., air filtration system and monitoring capabilities, EVA interfaces, etc.) will need to provide sufficient dust control and this will be demonstrated and refined during the lunar missions and be directly applicable to subsequent missions to Mars.

Finally, and perhaps one of the most important aspects of commonality for the crew cabin and other lander systems for Mars, is the operational experience and the lessons learned from the design and operations of the lunar human landing system. Many contingencies that arise during the lunar missions can be mitigated due the Moon's relatively close proximity to Earth. This will allow for the development and implementation of a Mars crew cabin with the reliability and verified functionality needed for the much longer and more distant missions to Mars.

4. Other Moon-Mars common investments

Since the dawn of the Space Age, missions to the Moon have been seen as the necessary first step to more difficult human missions to Mars. In addition to the lunar and Mars landers discussed earlier, launch vehicles, deep-space transportation, surface systems and logistical supply strategies and operations needed for Mars missions will be developed and tested on and around the Moon before the first crew leaves the gravitational sphere of influence of the Earth-Moon system.

4.1 Launch vehicle development

First, a lunar program will drive the need for large launch vehicle development. The physical size and mass of HLS-class landers, along with the cargo and logistics needs of a sustainable lunar surface base camp, will drive larger and more capable launch solutions, larger fairing size and on-orbit assembly, fuel transfer and cryogenic fuel management technologies. Both NASA and its commercial partners are currently pursuing each of these capabilities and critical technologies.

4.1.1 Space Launch System

NASA designed the super heavy-lift Space Launch System (SLS) as the world's most powerful rocket for safely sending humans on missions to deep space. For Artemis III, SLS will launch crew in the Orion spacecraft out to lunar orbit where they will meet up with the human landing system for their trip to the surface.

An evolvable vehicle with an upgrade path that that will increase mass delivered to trans-lunar injection (TLI) from an initial capability of 27 metric tons to an ultimate capability of at least 46 metric tons, SLS can deliver more payload directly to TLI than commercial launch vehicles. In addition, each variant in the vehicle series—Block 1, Block 1B and the ultimate Block 2—can be configured to launch Orion or with large-diameter payload fairings. The Block 1B and Block 2 crew vehicles can accommodate a co-manifested payload up to 10 metric tons in a Universal Stage Adapter (USA) that provides volume equivalent to an industry-standard 5-meter-class payload fairing. The Block 1B and Block 2 vehicles can be outfitted with 8.4-meter diameter payload fairings in varying lengths and engineers are preserving the option of a 10-meter diameter fairing for the vehicle. Large volume and wide diameters in SLS payload fairings enable the design of landers with lower centers of gravity for greater stability and larger cargo delivery to the Moon for sustainable architectures and for initial crewed Mars landings. In addition, the paralleled volume facilitates design of comfortable crew habitat modules.

4.2 Deep space transportation and habitation

In-space propulsion and deep space habitation will be necessary to transport crews to cislunar space and support their presence there. These same elements and their associated technologies will be critical for the transit of crews to and from Mars. Through the development of the lunar Gateway, NASA is taking the first steps to establish both of these propulsion and habitation technologies, and test crewed, long-duration, deep space operations.

4.3 Surface systems

On the lunar surface, systems will be deployed to test mobility systems, surface habitation, surface power systems, deep space communications, EVA and ISRU systems that will have a great deal of technology and operational commonality between the Moon to Mars surfaces. The capabilities that will enable sustainable lunar surface operations and provide reliable surface power, more capable EVA systems with greater mobility, high-reliability life-support systems, long-range pressurized and unpressurized rovers and ISRU systems that can be incorporated into the architecture's critical path and ensure mission success.

4.4 Logistics

As NASA's Artemis program transitions from early missions to a more sustained program, the human landing systems will transition to more reusable and sustainable operations, utilizing refueling and logistics transfer at the Gateway and on the lunar surface. Logistics services at Gateway will eventually extend to the lunar surface with delivery of pre-positioned surface assets and logistics modules. Refurbishment and repair of sustainable lunar systems will teach us how to build more reliable and robust Mars vehicles that will be more self-sufficient and able to keep both spacecraft and crews healthy for longer duration missions.

5. Conclusion

As NASA seeks to land the first woman and next man on the Moon, the Agency is using a Moon-to-Mars approach to develop, test and evolve the technologies and capabilities needed for further deep space exploration [16]. The Human Landing System (HLS) Program is taking a similar approach with its common Moon-Mars lander investments such as propulsion, precision landing and crew cabin design and operation. Other related common Moon-Mars investments include launch vehicle development, deep space transportation and habitats, surface systems, and logistics. The Program's initial and sustaining human landing systems provide parallel development toward landing the first humans on Mars.

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